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Combustion performance and emission characteristics of a diesel engine under low-temperature combustion of pine oil–diesel blends

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ABSTRACT

Pine oil is a biofuel derived from pine trees; its cetane number, kinematic viscosity, and boiling point are lower than those of diesel. Because of its inherent oxygen content, high calorific value, and good solubility, pine oil is considered as a potential alternative of diesel. In this work, we investigated the combustion and emission characteristics of pine oil–diesel blends in a high-speed four-cylinder turbocharged diesel engine under different loads and exhaust gas recirculation (EGR) rates. Four fuels, diesel blended with pine oil in proportions of 0%, 20%, 40%, and 50% (named as P0, P20, P40, and P50, respectively), were tested. The results show that when the load ranged from 40% to 100%, the equivalent brake specific fuel consumption (BSFC) of P50 was only 2.08–3.5% higher than that of P0, whereas that of P20 was <1% than pure diesel. The addition of pine oil to diesel decreased the soot emission, but NO_x emission increased. For pine oil–diesel blends, with the increase in the EGR rate from 0 to 24.6%, the variations in the soot, CO, and THC emissions were not obvious, whereas the NO_x emissions significantly decreased. Under the same EGR rate, with the increase in the proportion of pine oil, the NO_x emissions increased; the effects of an increase in the EGR rate on the NO_x emissions were higher than an increase in the pine oil fraction in the blend. When the EGR rate exceeded 24.6%, the soot, CO and, THC emissions sharply increased. However, it is possible to significantly reduce the soot emissions at a high EGR rate by increasing the blend proportion of pine oil.

1. Introduction

With increasing energy consumption and environmental pollution, the development of clean renewable fuels and new combustion technologies to satisfy more stringent emission regulations has become a hot research topic, particularly in the field of contemporary internal combustion engines. Recently, biofuels have received much attention as clean and renewable fuels [1–3], particularly ethanol [4–6], n-butanol [7–9], polyoxymethylene dimethyl ethers (PODE) [10–12], and biodiesel [13–15] are the most representative biofuels.

Biofuels have many advantages as alternative fuels for diesel engines [16–20]. They are biodegradable and are obtained from biological raw materials. Furthermore, they contain inherent oxygen that decreases the contents of aromatic hydrocarbon and sulfur as well as exhaust emissions. Therefore, it is essential to investigate the combustion and emission characteristics of diesel engines fueled with biofuels. Because most of the biofuels can be used in an engine without modification, they have been explored globally as mixed components or diesel fuel substitutes in automotive diesel engines [21–23]. Many experiments have been conducted to investigate the combustion and emission characteristics of diesel engines fueled with biofuels [24–27].

Diesel engines are widely used in various fields because of their good economic performance and low emission characteristics. However, the uncontrollable PM and NO_x trade-off relationship of the diesel engines simultaneously threatens both the environment and public health. This issue is solved using many advanced technologies such as HCCI combustion [28,29], PCCI combustion [30,31], and LTC [32,33]. LTC has been proved to be a practical method to simultaneously decrease both the soot and NO_x emissions. However, previous studies showed that the soot emission first increased and then decreased as the exhaust gas recirculation (EGR) rate increased, creating a region called soot-bump that was difficult to eliminate [34,35]. In the past few years, because of the relationship between NO_x and soot emissions, much attention has been paid to LTC in compression-ignition engines.

Extensive experimental studies on diesel engines fueled with biofuel–diesel blends have shown that alcohols, esters, biodiesel, and vegetable oil are promising alternative fuels [36–39]. Rajesh

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Kumar et al. [40] investigated the emission of dimethyl carbonate, iso-butanol, n-pentanol, and diesel blends in a single-cylinder DI diesel engine. The results indicate that both the smoke and NO_x emissions decreased simultaneously, whereas the HC and CO emissions increased. Devan and Mahalakshmi [41] studied the methyl ester of paradise oil–eucalyptus oil blends in a diesel engine. The experimental results showed that the smoke, HC, and CO emissions of Me50-Eu50 decreased by 49%, 34.5%, and 37%, respectively. Corsini et al. [42] investigated the performance and emission characteristics of a diesel engine fueled with vegetable oil. It was found that the soot and particulate emissions significantly decreased.

Besides ethanol, n-butanol, biodiesel, and vegetable oil, studies have been conducted on pine oil obtained from pine trees in diesel engines [43]. Unlike other alcohol-based fuels, the heat value of pine oil is higher, making it an appropriate biofuel for diesel engines. Moreover, its lower viscosity and boiling point contribute to fuel atomization and vaporization [44]. Terpineol ($C_{10}H_{18}O$) and pinene ($C_{10}H_{16}$) are the major components of pine oil. Their molecular structures show that pine oil is an oxygenated fuel. Moreover, pine oil has a better miscibility with diesel than ethanol and n-butanol.

The combustion and emission characteristics of pine oil–diesel blends have been studied. Vallinayagam et al. [45] studied pine oil–diesel blends in a single cylinder, direct injection diesel engine. The results showed that fueling with 100% pine oil under the full load condition decreased the CO, HC, and smoke emissions by 65%, 30%, and 70%, respectively, whereas the NO_x emission increased. Vedharaj et al. [46] tested combustion and emission characteristics of a cylinder diesel engine fueled with pine oil–biodiesel blends. Experimental results showed that the 50% pine oil–50% biodiesel blend had the optimum performance. Under the full load condition, the CO, HC, and smoke emissions were 18.9%, 8.1%, and 12.5% lower than diesel, respectively, and the NO_x emission was comparable to that of diesel. Yang et al. [47] investigated the emission characteristics of pine oil blend in a diesel engine equipped with SCR and catalytic converter. The brake thermal efficiency increased with the increase in the blending ratio of pine oil. The CO, HC, smoke, and NO_x emissions decreased by 67.5%, 58.6%, 70.1%, and 15.2%, respectively.

The abovementioned discussion clearly shows that pine oil is a promising alternative fuel for diesel engines. Nevertheless, the effects of pine oil–diesel blends on the combustion and emission characteristics of a diesel engine under low-temperature combustion with different EGR rates have not been investigated. Thus, the effects of pine oil–diesel blends on the combustion and emission characteristics of a light-duty diesel engine with different EGR rates were investigated in this study.

2. Experimental apparatus and procedures

2.1. Test engine and apparatus

The test was conducted using a four-cylinder diesel engine. The major parameters of the engine are shown in Table 1, and the test system is shown in Fig. 1.

Table 1
Technical specifications of test engine.

Model	Specification
Number of cylinders	4
Cylinder diameter (mm)	85
Number of valves	16
Stroke (mm)	88.1
Displacement (L)	1.99
Maximum torque (N m)	296
Compression ratio	16.5
Rated Power (kW)/Speed (r/min)	100/4000

As shown in Fig. 1, the engine speed was maintained at 1800 rpm (corresponding to the maximum brake torque conditions) in this test. The cylinder pressure was measured using a pressure sensor (Kistler 6052CU20). The pressure was recorded with a step of 1 crank angle increment, and 200 consecutive pressure cycles were measured and stored at each operating point. The fuel injection system was controlled using a software (INCA). The naturally aspirated engine's intake pressure was 0.15 MPa, and the intake temperature was (30 ± 2) °C. The EGR rate was controlled using the EGR value. The EGR rate and exhaust gas emission were measured using a Horiba MEXA 7500DEGR emission bench. The soot emission was measured using an AVL 415S smoke meter, and the particle emission was measured using a Cambustion DMS500 particle analyzer. The uncertainties of the apparatus are shown in Table 2.

2.2. Test fuels

Four types of fuels were tested in this study. Among them, diesel fuel (P0) was used as the base fuel for comparison. Three other fuels were obtained by blending pine oil with the base fuel. They were denoted as P20, P40, and P50, containing 20%, 40%, and 50% (v/v) of pine oil, respectively. The pine oil used in this experiment was produced by Hexing chemical Co., Ltd. of Jiangxi, China. The key properties of the tested fuels are shown in Table 3.

2.3. Operating conditions and test procedure

The engine speed was fixed at 1800 rpm corresponding to the maximum torque speed. During the engine test, the cooling water temperature was maintained at a stable value of 85 ± 3 °C using PT-100 temperature sensors. The inlet air temperature was (30 ± 2) °C, and the inlet air pressure was 0.15 MPa. P0, P20, P40, and P50 fuels were tested. The experiments were carried out in the following two steps:

The first step of the experiment was a load performance test. The EGR rate was set at zero, and other control parameters were based on the same ECU MAP calibration. Then, the engine was loaded using an electric eddy current dynamometer in steps of 20%, ranging from 20% load to 100% load.

The second step of the experiment was an EGR test. The EGR rate was changed by adjusting the corresponding valve. The BMEP, injection timing, injection pressure, and intake pressure were fixed at ~0.7 MPa (40% load), −6° CA ATDC (after top dead center), 120 MPa, and 0.15 MPa, respectively. The EGR rate was changed from 0 to 37.5% until the stability of the engine was lost. The control parameters, performance, and emissions results were recorded for off-line analysis.

In each test, the engine was run for a few minutes before performing the measurements to allow the CO_2 concentration and temperatures of the exhaust gas, cooling water, and lubricating oil to reach a steady state. The gaseous emissions were continuously measured for 5 min, and the steady-state tests were repeated twice to ensure reproducibility.

Moreover, the low heating value (LHV) was different for each test fuel; thus, the equivalent brake specific fuel consumption (BSFC) was used and calculated using the following formula:

$$BSFC_{equivalent} = (BSFC_{blends} * LHV_{blends})/LHV_{diesel} \quad (1)$$

3. Experimental results and analysis

3.1. Effect of different loads on the combustion characteristics of pine oil–diesel blend fuels

Fig. 2 shows the equivalent BSFC of the four fuels under different loads. As the load increased, the equivalent BSFC first decreased